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Special Report 85-17

October 1985





US Army Corps of Engineers

Cold Regions Research & Engineering Laboratory

Determining the effectiveness of a navigable ice boom

Roscoe E. Perham

AD-A162



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36 1 2

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION	READ INSTRUCTIONS BEFORE COMPLETING FORM	
1. REPORT NUMBER	2. GOVT ACCESSION NO.	S RECIPIENT'S CATALOG NUMBER
Special Report 85-17	111.2162	726
4. TITLE (and Subtitle)		5. TYPE OF REPORT & PERIOD COVERED
DETERMINING THE EFFECTIVENESS A NAVIGABLE ICE BOOM	OF	
A NAVIGABLE ICE BOOM	'	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(a)		8. CONTRACT OR GRANT NUMBER(s)
Roscoe E. Perham		NCE-1A-80-28EK
9. PERFORMING ORGANIZATION NAME AND ADDRESS		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
U.S. Army Cold Regions Research and		
Engineering Laboratory		CWIS 31354
Hanover, New Hampshire 03755-1290		12. REPORT DATE
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Engineer District, Detroit,		
and Office of the Chief of Engineers,	1	October 1985
Washington, D.C. 20314		30
14. MONITORING AGENCY NAME & ADDRESS(If differen	t from Controlling Office)	15. SECURITY CLASS. (of this report)
		Unclassified
		15a. DECLASSIFICATION DOWNGRADING
		SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)		
Approved for public release; distribution	on is unlimited.	}
17. DISTRIBUTION STATEMENT (of the abetract entered	in Block 20, if different fro	m Report)
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary ar	nd identify by block number)	,
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Ice control		ł
Winter navigation		
20. ABSTRACT (Continue on reverse side if necessary on		
The performance of a navigable ice bo	om was studied by	
the leading edge of the unconsolidated		
directly downstream of the boom. Ice		
from 1975-76 through 1978-79 for the	St. Marys River at	Sault Ste. Marie, Michigan. The
ice cover progression rate was highest the channel was estimated to have a tl		
During early winter the ice discharge		
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for the four years. Model tests for this site had indicated that without an ice control structure of any type, an ice release of 63,000/m³ per ship passage could be expected; with an ice boom the release would be 12,300 m³ per ship passage. If a 100% effective boom releases no ice at all, then the measured rate indicates that the boom is 92% effective. On-site observations and time-lapse movies provided partial verification. Ice flowed down the ship track and through the navigation opening fairly often. Occasionally ice came over the boom in response to ship movements and natural causes.

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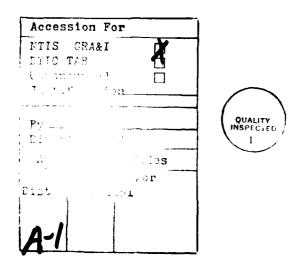
PREFACE

This report was prepared by Roscoe E. Perham, Mechanical Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

The data were collected and some compilation was done under a study funded by the U.S. Army Engineer District, Detroit, Michigan, under contract no. NCE-1A-80-28EK, St. Mary's River Ice Boom Monitoring. Subsequent effort was funded by the U.S. Army Corps of Engineers Civil Works Project, CWIS 31354, Ice Boom Mechanics.

The author thanks James Sirois of CRREL and Roger Gauthier, Ron Pearce, Frank Killips and Ken Brown of the Detroit District for assisting in this project. This report was technically reviewed by Darryl Calkins, James Wuebben and Dr. Jean-Claude Tatinclaux.

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DETERMINING THE EFFECTIVENESS OF A NAVIGABLE ICE BOOM

Roscoe E. Perham

INTRODUCTION

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A variety of ice problems were encountered in the St. Marys River due to winter navigation. To minimize ice accumulation problems, a floating timber ice boom was installed at the outlet of Soo Harbor, at Sault Ste Marie, Michigan, leading into the 183-m-wide and 9.1-m-deep Little Rapids Channel. The 76-m-wide navigable opening of the boom is centered on the navigation course number 2 shown in Figure 1. The location of the ice boom and the size of the opening were selected after a study of various ice control arrangements in a physical model (Cowley et al. 1977). The structure was considered to be fully successful because the required river water levels and flows could be maintained during the entire winter.

The model study developed a measure of the effectiveness of an ice control structure. A simulated ice cover made of plastic pellets weakly bonded together was constructed on the 1:120 scale model. The pellet size was equivalent to a full-scale ice thickness of 0.3 m. A self-propelled model ship was piloted through the cover by remote control. The ice discharge from the harbor was collected downstream and measured. The average quantity of ice released per vessel passage for natural conditions was the equivalent of 63,000 m³ per ship passage. The model ice control structure decreased this value to the equivalent of 12,300 m³ (434,000 ft³) per ship passage, or about 20% of the uncontrolled value. The model control structure, therefore, had an effectiveness of 80% for reducing the ice discharge per vessel passage.

Determining the ice discharge through and over an ice boom is much more difficult in the field because the ice cannot be measured easily or safely. The primary method used by the Detroit District, U.S. Army Corps of Engineers (1979) was to monitor the ice movements near the boom by time-

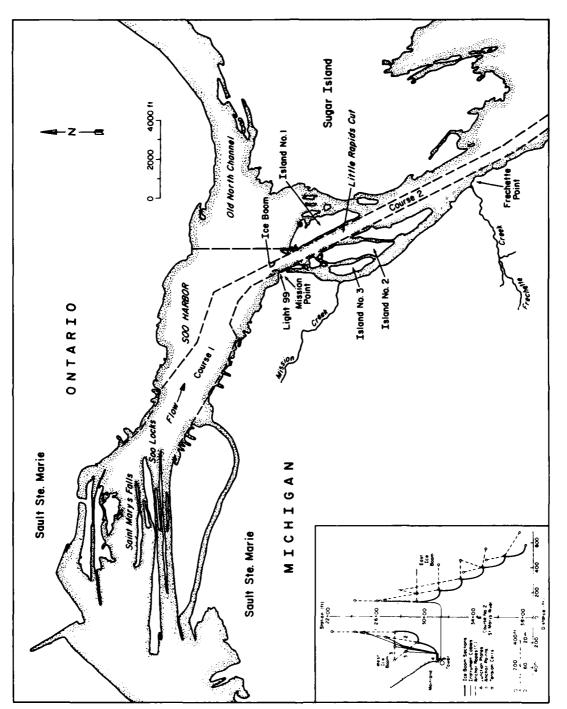


Figure 1. Soo Harbor and Little Rapids Channel.

lapse movie camera and estimate ice quantities from the record. For additional documentation, oblique photographs were taken of the St. Marys River on a weekly basis.

For the present study, however, the ice discharge was determined by observing the location of the upstream edge of the unconsolidated ice cover in a reach of the Little Rapids Channel having a fairly constant cross-sectional area. It was assumed that a unit movement of the ice edge is caused by a particular quantity of ice coming from Soo Harbor. This report provides the ice edge data and discusses its accuracy and merits compared to the time-lapse information. Unconsolidated ice thickness measurements and ice growth in the area are also discussed.

Soo Harbor

Soo Harbor is quite large and is irregularly shaped on the Canadian side (Fig. 1). Its area is approximately 3.7×10^6 m² (40×10^6 ft²). The St. Marys Falls reach is generally open water for most of the winter and has an area of about $0.6-0.7 \times 10^6$ m² ($6-7 \times 10^6$ ft²). The opposite (eastern) limit of the harbor for the purposes of this study is a line leading due north from the ferry dock at Sugar Island to the Canadian shore.

Two areas in Soo Harbor remain ice free throughout the winter: the St. Marys Falls downstream of the three hydroelectric plants and a thermal outfall of the Algoma steel plant in the northwest corner of the harbor. The most complete ice cover seen was approximately 3.3×10^6 m² (35×10^6 ft²), or 88% of the harbor. The harbor was usually considered to be fully ice covered, however, when the ice area was smaller, because ship activity and atmospheric disturbances could keep the size of these areas changing by 10% or so. For instance the area of the 4.1-km-long ship track was approximately 0.13×10^6 m² (1.4×10^6 ft²). Sometimes the track is covered with ice and sometimes it isn't.

Table 1. Date of complete ice cover on Soo Harbor.

Winter	Ice cover complete	Ice cover stable	Ice thickness above west boom (m)
1975-76	15 January	22 January	? -0.13
1976-77	28 December	29 December	0.13
1977-78	10 January	ll January	0.18
1978-79	7 January	8 January	0.18-0.30

Table 1 gives the dates when Soo Harbor was frozen over and the dates when the complete ice cover appeared stable. The term "stable ice cover" for the harbor area means that the overall ice cover dimensions remained the same, even though much of the cover was fragmented.

Little Rapids Channel

The Little Rapids Channel (Fig. 2) is a man-made navigation improvement connecting Soo Harbor with Lake Nicolet. It has a 183-m- (600-ft-) wide channel excavated to a minimum depth of 8.2 m (27 ft). The narrowest portion of the channel is at its upper end, where Island No. 1 was cut in two. This part of the channel has a cross-sectional area of 1609.8 m² (17,327.4 ft²) at a low water datum elevation of 176.05 m (577.6 ft) and reaches from the upper end of Island No. 1 approximately to navigation light 95, a distance of 1500 m (5000 ft). This cross-sectional area is approximately the same for 250 m (820 ft) or so above and below these points. The natural width of the reach between Island No. 4 and Frechette Point is greater than that at Frechette Point. How this convergence affects the flow is unknown. The cross-sectiona' flow area at Frechette Point is 2407.3 m² (25,912.4 ft²) at a low water datum of 176.02 m (577.5 ft). The ratio of the Little Rapids Cut area to the Frechette Point area is 0.67. One would expect, therefore, that the flow velocities in the

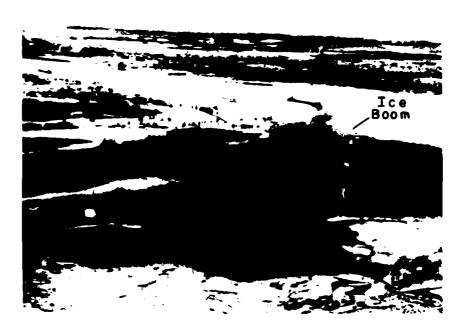


Figure 2. Little Rapids Channel.

upper half of the channel would be roughly 50% higher than those in the lower half. Further details of the channel are given in Appendix A.

DATA COLLECTION AND ANALYSIS

Ice Edge Progression

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The water velocity in the Little Rapids Channel is too high for an ice cover to grow across it from shore to shore. Instead an ice cover must first form downstream in the lower velocity reaches of Lake Nicolet and bridge across the channel about 3.5 km (2.2 miles) below the ice boom. The ice floes, brash ice and frazil slush moving downstream are stopped by this ice bridge, and the incoming ice causes the leading ice edge to progress upstream. The ice entering the channel usually comes down the shipping track as brash and slush ice, but sometimes it moves over the boom as broken sheets. Examples of these types of ice at the navigation opening are shown in Figure 3. The ice movements are triggered primarily by wind and ship activity and occasionally by water level fluctuations.

During the first winter of ice boom operation, 1975-76, my efforts were concentrated on measuring forces on the boom (Perham 1977), but I also attempted to estimate the area of the ice cover in Soo Harbor and Little



a. Ice floes generated by a passing ship.

Figure 3. Moving ice at the boom opening.



b. Brash ice and ice floes mixed with slush accumulations. The flow is from left to right.

Figure 3 (cont'd). Moving ice at the boom opening.

Rapids Channel. From light tower 99 at Mission Point, one can see up to the Soo Locks and down the Little Rapids Channel to Frechette Point 3.5 km (2.2 mi) away. To help quantify ice coverage in the harbor and the channel, a map of the channel approximately 1.2 km upstream and downstream of the boom was made. Station markers were installed at 152-m (500-ft) intervals along the Sugar Island side of Little Rapids Channel. Sketches of ice coverage were made on the maps on a regular basis and at the same time the location of the ice edge in Little Rapids Channel was noted. Some data were also available from oblique aerial photographs acquired by the Detroit District (Fig. 2).

It was hoped at first that the ice edge location could be monitored the full distance from Frechette Point to the ice boom, but a careful look at the data showed several inconsistencies at points that far away. The data from near the lower end of Island No. 4 to the ice boom, however, were reasonably good.

The progression of the ice edge in the Little Rapids Channel was monitored for four years (Appendix A), and the data are plotted in Figure 4. Data were taken visually by observers. The curves are jagged once the ice edge nears the ferry track; this is almost exclusively due to ice-breaker activity.

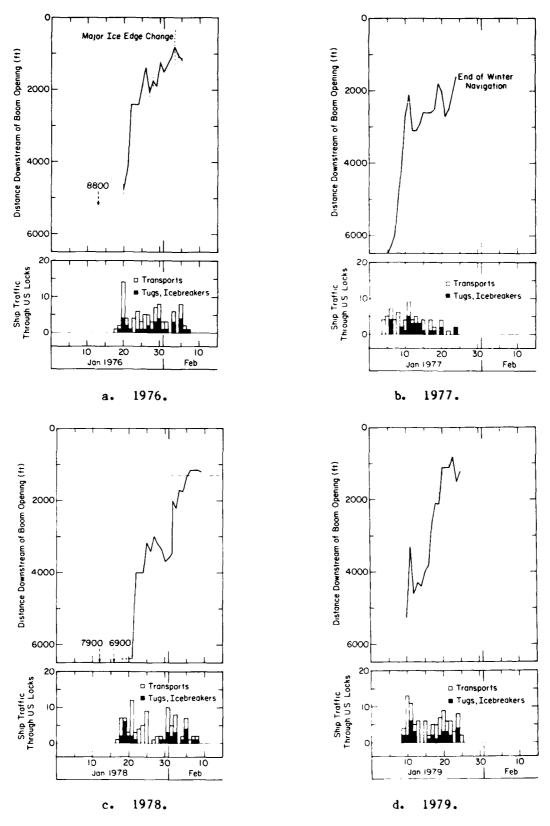


Figure 4. Progression of the ice edge in Little Rapids Channel.

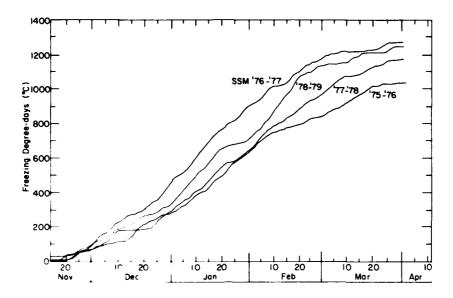


Figure 5. Freezing degree-days at Sault Ste. Marie.

There are fairly obvious trends in these curves. The early portion of each curve is very steep, showing that the ice edge had moved rapidly. During this period the air temperatures remained fairly constant, but of course they varied from one year to the next. The highest temperature was -8.6°C, during the winter of 1977-78, and the lowest was -19°C, during 1976-77; the average for the four years was -15°C. Curves of degree-days of freezing for the four winters are in Figure 5. As the ice edge approached the ferry track, its upstream progress would slow. This may have been due to a reduction in the rate at which ice arrived at the ice edge but it was also due to the action of ice breakers and ships. Later in the winter the ice edge location would move upstream and downstream while generally moving slowly away from the ferry track. At the time of spring ice breakup, the ice edge moved quickly downstream.

The rate of ice edge progression can be determined from the slope of the ice edge location and time curve. The most important factor, though, is how this affects ice volume, because the final determination of effectiveness in this situation is the ratio of the ice volume to the number of ship passages. To determine ice volumes, one must know the depth and porosity of ice in the unconsolidated ice cover.

Unconsolidated ice cover thickness

Very few measurements of ice thickness have been made in the Little Rapids Channel. During the second week of February 1974, Voelker and Friel

(1974) obtained values at various cross sections from 270 to 1130 m below the ice boom location. This was done after shipping stopped for the winter and is an example of pre-ice-boom conditions. The thicknesses varied wide-ly but averaged between 1.2 and 2.0 m. Ships required ice breaker assistance at times during the 1974 winter navigation season in order to transit the Little Rapids Channel. The substantial thicknesses are probably due more to ice breaker and ship action than to flow effects on the unconsolidated ice cover. Working from a boat in 1979, I found the thickness of the ice edge near the ferry track following a period of typical ship activity to average 0.92 m (3 ft). Ship passages for the previous week were 10 upbound and 13 downbound transports and 6 upbound and 6 downbound U.S. ice-breakers and work boats.

On 17 February 1978, Corps of Engineers personnel attempted to measure the discharge across a section of the channel at Frechette Point but could complete only three of seven stations due to the extremely difficult ice conditions. The ice thickness profile at that time indicated that approximately 15% of the total cross sectional area of the channel was filled with a combination of fixed and rafted ice. This value is equivalent to an average ice thickness of 0.90 m.

On the 23 and 24 February 1979, ice thickness was again measured by Corps personnel at Frechette Point, and these measurements showed substantial differences over the section. The ice was thicker at the edges of the ship track but had only a 1.22-m maximum. The minimum thickness of 0.15 m was in the approximate center of the ship track. The average ice thickness was 0.52 m. There were similar variations in measurements obtained on 8 and 10 February 1972 by the Corps, but the average thickness then was 0.91 m.

Vance (1980) measured brash ice thicknesses in the ship track farther downstream in the Middle Neebish Channel and in Lake Nicolet. He measured thicknesses from 1.07 to 1.52 m near Stribling Point, where the flow area varies from 2260 to 2940 m². On Lake Nicolet, where the flow area is as great as $11,000 \text{ m}^2$, the brash ice in the channel was 1.22 m thick and the solid ice thickness was 0.67 m. These findings show how ship transits as well as flow velocities lead to a thickening of the unconsolidated ice masses.

Because of the shortage of data on ice thicknesses in the Little Rapids Channel, I estimated the ice thicknesses using the theories described in the Appendix B. The ice thickness was estimated to be approximately 0.91 m or greater in Little Rapids Cut. It was assumed that the unconsolidated ice cover has a porosity of 30%, which is a rough estimate based on studies by Sandkvist (1981) and personal observations in other areas.

Table 2. Daily ship traffic through the U.S. Locks, upbound and downbound totals, during the period of major ice edge movement in Little Rapids Cut for four winters.

	1975-1976		19	76-1977	19	77-1978	1978-1979		
	Trans-	Tugs,	Trans-	Tugs,	Trans-		Trans-	Tugs,	
Jan 4			4	0					
5			5	0					
6			3	4					
7			4	0					
8			6	0			_	_	
9			0	2			2	2	
10			3	1			11	2	
11			4	5			5	6	
12			1	3			2	3	
13			2	3			6	0	
14			0	3			0	0	
15			3	1			6	0	
16			0	0		_	1	1	
17			3	1	1	0	3	2	
18	1	0	1	1	5	2	4	1	
19	1	1	0	0	1	6	5	2	
20	10	4	2	2	1	2	6	3	
21	2	2	0	0	10	2	3	3	
22	0	1	i	0	2	1	4	2	
23	4	0	0	0	4	0	3	0	
24	5	1	0	2	5	0	4	4	
25	2	1			9	0	2	0	
26	4	1			0	0			
27	3	2			0	0			
28	2 4	3			ı	0			
29	4	3			2	0			
30 31	2	4			1	1			
		1			0 7	1			
Feb 1	2 0	0			•	3			
2	3	3			3	2			
4	0	0			5 0	3 0			
5	4	4			1				
6	1	4			3	1 4			
7	0	1) I	0			
8	4	2			1	1			
ð	4	Z			1	1			

Ship Traffic

The source of information about ship traffic is the logbook for the U.S. locks operated by the U.S. Army Corps of Engineers, Soo Area Office. I have grouped ships into two categories: transports, which vary considerably in size and power, and icebreakers and tugs or work boats. The transport ships have the greatest effect on the Soo Harbor ice cover, and at times they need to have an icebreaking tug assist them, particularly at the angle bend between course 1 and course 2.

The transports varied from 99 m long x 15 m wide (324 x 49 ft) to $305 \times 32 \text{ m}$ (1000 x 105 ft); the average length was about 213 m (700 ft). The transports were mainly iron ore carriers, but there were occasional fuel carriers (Perham 1984).

Most of the ship lockages resulted in a transport passing through the boom, but occasionally one stayed in the harbor. Most ships transited the boom on the same day that they locked through, but some did not. Keeping track of the icebreakers and tugs is quite difficult because they could pass through the navigation opening several times without having to go through the locks. In any case the main contributor to ice losses from Soo Harbor was the transport ships, and the ice losses are considered to be related solely to their passages. Table 2 lists the number of ship lockages per day during the periods of rapid ice edge progression for each of the four winters. The quantities are also plotted in Figure 4.

Ice discharge per ship

The ice discharge per ship is calculated by converting the change in location of the ice edge to an equivalent value of ice quantity and dividing that value by the number of transport ship passages in the period during which the location changes took place. Figure 4 shows that the ice edge sometimes progressed upstream very rapidly, sometimes remained stationary, and occasionally moved downstream. The downstream movement was probably due to transport and icebreaker activity (especially the latter), but sometimes an unconsolidated ice cover will collapse or telescope by itself and become thicker, enabling it to withstand the flow forces. At times icebreakers have worked the full length and breadth of Little Rapids Cut with the same effect. It is not possible to say exactly what caused the ice edge recession or apparent inactivity.

Table 3. Calculated values of ice discharge per ship passage based on ice edge progression in Little Rapids Cut.

		Selected	Loca of the	tion e edge	Number*	Ice dis	-
Winter	Period	dates	(ft)	(m)	of ship		(m ³)
1975-76	IEP† and	20 Jan	4750	1448	23-1/2	180,000	5,090
	Dominant	26 Jan	1400	427			•
		20 Jan	4750	1448	12	247,000	6,990
		22 Jan	2400	732		•	·
		21 Jan	4100	1250	14	243,000	6,880
		26 Jan	1400	427			
		21 Jan	4100	1250	2**	1,071,000	30,300
		22 Jan	2400	732			
1976-77	IEP and	5 Jan	6500	1981	20-1/2	270,000	7,660
	Dominant	ll Jan	2100	640			
		7 Jan	6000	1829	13	378,000	10,700
		ll Jan	2100	640			
1977-78	IEP	20 Jan	6400	1951	50	127,100	3,600
		5 Feb	1350	411			
		21 Jan	6400	1951	10**	302,000	8,560
		22 Jan	4000	1219			
		31 Jan	3600	1097	11-1/2	208,000	5,900
		3 Feb	1700	518			
	Dominant	20 Jan	6400	1951	30-1/2	140,000	3,980
		27 Jan	3000	914			
1978-79	IEP	10 Jan	5250	1600	40-1/2	129,000	3,650
		20 Jan	1100	335			
		10 Jan	5250	1600	8	307,000	8,700
		ll Jan	3300	1006			
	Dominant	14 Jan	4400	1341	22	189,000	5,400
		20 Jan	1100	335			

^{*} Includes average of number of passages on first and last days of period, which can yield values of $1/2\ \text{ship}$.

There are brief periods when the ice discharge per ship is higher than the average for a longer period of time. It is thought that these higher values are a real effect and are the upper limit for the ice control system. Ordinarily, average values for longer periods of time are more credible than short-term values, but this may not be the best way to interpret the present results.

[†] Ice edge progression period.

^{**} Estimated maximum, 1 ship fewer is a possibility.

Table 3 contains values of ice discharge for the four winters. These data were analyzed in several ways. An ice edge progression period (IEP) was selected to include most of the times when the ice edge moved rapidly upstream in the cut. In addition, a dominant period was designated to represent a period of time that included a significant amount of ice movement and a significant number of ship passages. The remaining periods shown in Table 3 are shorter and generally represent the most rapid ice edge progressions. Unless otherwise indicated, the total number of ships for a period includes an average of ship passages on the first and the last day of a period. The reason for this is that ships passing late in the day would not have influenced the ice edge location established for that day. This averaging sometimes yields values of 1/2 ship.

The last columns in Table 3 give the values for the ice discharge through the boom per transport ship passage. The dominant values vary from 3980 to 7660 m³/ship and have a four-winter average of 5530 m³/ship. These values, of course, are influenced by meteorological conditions, which can cause substantial ice movements. However, the ice cover is easier to move by wind and water currents after it is broken by the ships.

The maximum ice discharge for nondominant periods varied from 30,300 to 5,900 $\rm m^3/ship$. Ignoring these values and taking the average of maximum ice discharge for the five remaining nondominant periods, a value of 8370 $\rm m^3/ship$ is obtained.

Other evidence

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Time-lapse photography. An 8-mm movie that covered the ice edge progression period for the winter of 1978-79 was available. It shows the navigation opening and the ice cover above the booms including the ship track approximately up to the angle turn from course 2 to course 1. The film was exposed at a rate of 1 frame per 90 s and was viewed at 6 frames per s. It showed Soo Harbor exit conditions for approximately 8.5 hrs per day. During part of the movie, the view was obscured by "frost smoke" and snowfall.

The passages of large transport ships were easy to see, but those of Coast Guard vessels and work boats were not. From 10 to 24 January, 23 large vessels passed; in addition, there were about 16 small vessel transits. The vessels generally seemed to cause ice releases in proportion to their sizes. Not all vessels caused ice releases, but most transport ships

did during this period. These releases seemed to be typical ice runs containing slush ice, brash ice and ice floes (Fig. 3).

The average water velocity based on total river flows and previous under-ice water velocity measurements was 0.52 m/s (1.7 ft/s) in Soo Harbor. The speed of the ice run was assumed to be somewhat less, about 0.46 m/s (1.5 ft/s). The widest commercial vessels were 32 m (105 ft) wide, which controls the minimum width of the ship track, provided the ice sheet does not move laterally. An ice run rarely covered the whole width of the track, but it would often cover a third to a half of it. A typical ice run was estimated to be a mass 13 m (44 ft) wide and 0.13 m (0.43 ft) deep with a porosity of 50%. The length of time that it flowed was measured with a stopwatch from the movie and then converted to real time.

In addition to the ice moving in the ship track, a substantial quantity of ice moved over the boom as broken ice sheets. Some of this ice (measured from a work boat) was over 0.3 m thick. The volume of this ice was estimated from this thickness and the area that was seen to move over the west ice boom. Most of the sheet ice was released during the first week.

The total amount of ice released between 10 and 24 January was estimated to be 3.3×10^6 ft³ (9.3×10^5 m³). For the 23 commercial ships that were seen to pass, the ice release was therefore 4060 m³/ship (1.6×10^5 ft³/ship). Approximately 65% of this ice release went over the boom as solid sheet ice.

Ice Boom Logbook. A nearly continuous series of observations of ice runs in the ship track and ice movement over the booms were noted in the logbook kept at the ice boom site. These data were compared with those from the time-lapse photography, and they corroborated the photographic evidence: the logbook showed that the ice ran in the ship track for a total of 77,000 s, while the time-lapse movie showed that the ice ran for 80,000 s.

DISCUSSION

Ice generation in open water

A paradoxical situation exists in Little Rapids Cut. Heat transfer calculations show that enough ice could be generated in the open water there to nearly account for the ice edge progression rates. A value for water surface conductivity of $22.5 \text{ W/m}^2 \cdot \text{K}$ is often used but may be high for

this location (Devik 1944, 1948). The ice grown in the open water of Little Rapids Cut is frazil slush in form and does not develop into ice pans with strength and appreciable buoyancy. The typical situation is illustrated in Figure 2, which shows the ice edge at the lower end of Island No. 4 on 18 January 1978. There was no wind and the air temperature was -23°C. The change in the water surface from glassy to rough is probably due to developing frazil flocs. The ice was very porous, probably 90% or higher, and for ice such as this to remain at the ice edge, the water velocity must be quite low. According to Michel (1971), for the existing water depth of 9.54 m, the average velocity should be 0.48 m/s or less for frazil slush to contribute directly to ice edge progression. The average open water velocity for 1978 was 0.77 m/s. The other average velocities varied from 0.60 to 0.69 m/s. Frazil and snow slush will therefore be drawn beneath the ice edge. Some of the slush could be trapped in pockets between the tilted ice floes and contribute in a minor way to the ice edge progression rate. However, most of the slush moves downstream beneath the unconsolidated ice cover to be deposited at various locations in the icecovered channel and in Lake Nicolet. What happens to it is complex and will not be discussed here. Under certain circumstances these deposits can lead to flooding in Soo Harbor, but this did not happen during my study.

Ice Thickness

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The method described here for estimating the ice discharge is simple to implement and monitor. The main problem lies in determining the thickness and porosity of the unconsolidated ice cover that develops in the channel. The ice cover is unsafe to work on, so a radar system mounted on a helicopter is probably the best approach for measuring ice thickness. Ground truth measurements of ice thickness and brash ice sampling for determining porosity could be done safely from a work boat. In lieu of this, however, predicting ice thickness by theoretical means is acceptable. The methods in Appendix B are a conservative approach for estimating thickness.

Comparison with Other Ice Inventories

The results of this study differ from the findings of Daly and Weiser (1981), which were based on a review of films from time-lapse cameras scanning the ice boom area. The quantities found here are greater by approximately an order of magnitude. I'm not sure why their results were so low,

especially in light of the ice inventory in the U.S. Army Corps of Engineers (1979) report.

The time-lapse movies were reviewed by Corps personnel at the Detroit District and were analyzed for a section in their annual report on Soo Harbor water levels for the 1977-1978 and 1978-1979 seasons. The inventory gave no quantities other than general descriptions. It indicated that ice moved fairly often due to the passage of ships, but no quantities were given for these events. The observations were by daylight only. There were ship passages and ice movements at night too, as indicated in the ice boom logbook. For example, on 14, 15 and 16 January 1979 the inventory had "extremely light" or "light" ice flow through the opening, yet the ice edge progressed from 1310 to 790 m (4300 to 2600 ft) below the boom. The logbook data, however, showed that several ships passed by on the nights of 15 and 16 January and caused considerable ice losses from the harbor.

Comparison with Model Tests

The full-scale conditions used by Cowley et al. (1977) in the 1:120 model were a river flow of 2435 $\rm m^3/s$ (86,000 cfs) and an ice thickness of 0.3 m (1.0 ft). The model testing had turbulent flow in all of the navigation channels and beneath most of the ice cover.

One noticeable difference was the speed of the model ship, which was based on a full-scale speed of 1.3-2.2 m/s. The actual ship speeds varied from 0.85 to 5.6 m/s and averaged 3.7 m/s. This higher speed is bound to cause greater ice releases than lower speeds, but a detailed evaluation of this phenomenon is not possible. It is the larger ships that usually go faster through the ice. This effect could best be determined by model studies organized specifically for that purpose.

A second important difference was in the physical properties of the ice. The model ice cover remained broken after the model ship passed through; that is, it could not refreeze. Also, the model ice material, polyethylene, did not have the same cohesive properties as ice. However, since the material was in small pellets, the surface tension effects of the water may have simulated cohesion to some extent. Cowley et al. (1977) did not indicate that this effect was studied; instead, the observations concentrated on the larger fracture patterns and ice floe development. In addition, model ice was added to the model after each ship passage, but no thermodynamic correlation was given for the quantity used.

Cowley et al. (1977) operated their model ship so that it would break out more ice than they thought the normal ship operations would. However, full-scale ship operations often break out more ice than is necessary, for example, to get ships from Little Rapids Cut to the locks. Docks on both sides of the harbor were used fairly often and work boats were often seen widening the shiptrack. The model study, then, simulated the actual conditions fairly accurately.

The harbor ice cover was further stabilized by structures set in place two years after the ice booms were installed (Perham 1984). No attempt was made, however, to optimize the location or the type of structure used.

Ice Cover in Soo Harbor

Thermal effluents in the area reduce the thickness of the ice cover at various locations in Soo Harbor. They affect ice conditions in the Little Rapids Channel as well, but no data were obtained on this subject. Conceivably the quantity of heat input could vary appreciably from one day to another.

The thickness of the ice sheet in Soo Harbor was an important factor in the stability of the ice cover behind the boom. In early winter the thin ice sheets were easily broken by wind and wave effects and by water surface variations due to passing ships and river flow changes. The rather small pieces that were created easily moved out into ship track and down through the ice boom opening. Later, as the ice grew to over 0.3 m thick, it become more resistant to breaks, and when breaks occurred, the sections that formed were large and often unable to move into the ship track. The periods of rapid ice progression in Little Rapids Channel invariably occurred in early winter, when the harbor ice was relatively unstable.

Non-dimensional Parameter

Calkins and Ashton (1975) conducted a model study of the arching of ice floes at a boom opening in a small hydraulic flume using two sizes of square plastic blocks as the model ice. In addition to block size, the variables were opening size, water velocity, and areal concentration of the blocks. The blocks were fed mechanically onto the water surface upstream of the boom opening. The blocks would eventually arch across the opening and prevent more blocks from passing through.

As part of the test the researcher would break the arch mechanically, measure the time it took for the arch to reform, and measure the area of

the model ice released through the opening. The volume of ice released in these tests was proportional to the area because the ice thickness was constant. Calkins and Ashton presented the ice releases in non-dimensional form as A_r/b^2 , where A_r is the ice released per disturbance, and b is the opening size. They found that, on the average, A_r was equivalent to b^2 , or $A_r/b^2 \approx 1.0$ (Fig. 6). The results from other model studies are given in Table 4.

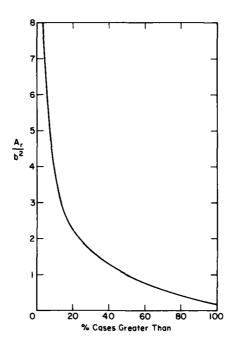


Figure 6. Area of ice released after disturbance of an arch. (After Calkins and Ashton 1975.)

Table 4. Values of A_{r}/b^{2} for hydraulic navigation model studies.

	Opening	size, b	_
Reference	(m)	(ft)	A_r/b^2
Acres American, Inc (1975)	76	250	6
Boulanger et al. (1975)	76	250	4
Arctec, Inc. (1978) Arctec, Inc. (1980)	69 69	225 225	3.5 2.7

A rough estimate of values for this parameter for the St. Marys River ice boom opening can be determined from the time-lapse photographs. They showed that $2.0 \times 10^5 \text{ m}^2$ ($2.1 \times 10^6 \text{ ft}^2$) of sheet ice and $4.9 \times 10^5 \text{ m}^2$ ($5.3 \times 10^6 \text{ ft}^2$) of brash and slush ice moved through the area. Twenty three commercial ships transited the opening during the period of movement; therefore $A_r/b^2 \approx 5$. However, sheet ice and brash and slush ice have quite different thicknesses and porosities. Converting the brash and slush area to an equivalent solid area before adding these together gives $A_r/b^2 \approx 2$.

This parameter can be calculated from the ice edge progression in Little Rapids Channel, but without much certainty. If the ice passing the boom is 0.3 m (1.0 ft) thick and has a porosity of 30%, the values of $A_{\rm T}/b^2$ are 2.9, 4.3, 2.2 and 3.0 for the four winters studied. These values correlate well with model tests. The best type of information would have been the area and volumes of ice passing the boom. However, the problem of calculating the area of the mix of ice floes, brash ice and slush ice would remain.

CONCLUSIONS

- 1. The effectiveness of the navigation ice boom at the head of Little Rapids Channel is substantially higher than predicted by the model study; i.e., average values of 5,500 to 8,400 m³ per ship were found in early winter compared with the 12,300 m³ per ship from the model study. Ice cohesion appears to be a major cause of this difference; there are several other factors that were not studied.
- 2. The equipment and techniques for measuring ice movements and accumulations need to be improved in order to quantify ice boom effectiveness.

RECOMMENDATIONS

- In further programs of this nature, a researcher or specially trained observer should be on site during the ice cover formation and stabilization periods to estimate the quantitites of ice released by passing ships. He should have assistance and equipment for determining ice thicknesses and porosities of brash and slush ice and of the unconsolidated ice cover.
- 2. The effects of thermal effluents should be evaluated to a reasonable extent for Little Rapids Channel.

 A better method should be developed for measuring the amount of ice beneath the ice cover in Little Rapids Channel and in Upper Lake Nicolet.

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APPENDIX A. LOCATION OF THE ICE EDGE IN LITTLE RAPIDS CHANNEL FOR FOUR WINTERS.

1975-197	16	1976-	1977		1977-197	18	1978	-1979
Date Lo	cation	Date	Location	Date	Lo	cation	Date	Location
	(ft)		(ft)			(ft)		(ft)
	0000	20 5 76	11600	10 7	70	7000	0 1 70	11600
13 Jan 76	8800	29 Dec 76	11000	12 Jan	/0	7900	9 Jan 79 10 Jan 79	
20 1 76	a. 4900	30 Dec 77	8000	16 Jan	70	6900	10 Jan 79	
20 Jan 76 a. n	4900	JO Dec //	8000	18 Jan		6400	II Jan / >	3300
20 Ion 76 n n	a. 4600	3 Jan 77	11600	21 Jan		6400	12 Jan 79	4600
20 Jan 76 p.m 21 Jan 76	4100	5 Jan 77	6500	22 Jan		4000	12 Jan 79	
22 Jan 76	2400	6 Jan 77	6300	23 Jan		4000	14 Jan 79	
23 Jan 76	2400	7 Jan 77	6000	24 Jan		4000	15 Jan 79	
24 Jan 76	2400	8 Jan 77	5000	25 Jan		3350	16 Jan 79	
25 Jan 76	1900	9 Jan 77	4000	26 Jan		3400	17 Jan 79	
26 Jan 76	1400	10 Jan 77	2700	27 Jan		3000		
		11 Jan 77	2100	28 Jan		3200	18 Jan 79	a.m. 260
27 Jan 76 a.m	n. 1900	12 Jan 77	3100	29 Jan	78	3350	18 Jan 79	p.m. 210
27 Jan 76 p.m	a. 2200	13 Jan 77	3100	30 Jan	78	3700	19 Jan 79	2100
28 Jan 76 a. n	n. 1600	14 Jan 77	2900	31 Jan	78	3600	20 Jan 79	a.m. 900
28 Jan 76 p.a	. 1900	15 Jan 77	2600	l Feb	78 a.m.	3450	20 Jan 79	p.m. 1300
29 Jan 76	1900	16 Jan 77	2600	l Feb	78 p.m.	2000	21 Jan 79	1100
30 Jan 76 a.m	a. 1200	17 Jan 77	2600	2 Feb	78	2200	22 Jan 79	a.m. 1000
30 Jan 76 p. n	n. 1300	18 Jan 77	2500	3 Feb	78	1700	22 Jan 79	
31 Jan 76	1500	19 Jan 77	1800		78 a.m.	1500	23 Jan 79	
1 Feb 76	1300	20 Jan 77	1600	5 Feb	78 p.m.	1200	24 Jan 79	
2 Feb 76	1100	21 Jan 77	2700	6 Feb		1150	25 Jan 79	
3 Feb 76 a.π	n. 1300	22 Jan 77	2500	7 Feb	78	1150	26 Jan 79	1700
		23 Jan 77	2000		7.0			1.00
3 Feb 76 p. a	a. 300	24 Jan 77	1600	8 Feb	/8	1150	28 Jan 79	
/ m.s. 74	1000	26 7 77	2100	10 8-1	70	1250	29 Jan 79	
4 Feb 76 a.m		25 Jan 77	2100		78 a.m.	1350	30 Jan 79	
4 Feb 76 p. n		26 Jan 77	1600 2100	10 Feb 11 Feb		1900 1350	31 Jan 79 1 Feb 79	
5 Feb 76 a.m 5 Feb 76 p.m		27 Jan 77 28 Jan 77	1900	ll Feb		1600	2 Feb 79	
6 Feb 76	900	31 Jan 77	1200	12 Feb	•	1200	3 Feb 79	
7 Feb 76	900	1 Feb 77	1600	13 Feb		1500	4 Feb 79	
8 Feb 76	1100	2 Feb 77	1600	14 Feb		1500	5 Feb 79	
9 Feb 76	1300	3 Feb 77	1600	15 Feb		1400	6 Feb 79	
				.,	. •		- 100	p.m. 1300
10 Feb 76	1200	4 Feb 77	2400	16 Feb	78	1300	7 Feb 79	•
11 Feb 76	1000	5 Feb 77	2500	17 Feb		1400	8 Feb 79	
12 Feb 76	1100	6 Feb 77	2600	18 Feb		1400	9 Feb 79	
13 Feb 76	1100	7 Feb 77	2300	19 Feb	78	1400	9 Feb 79	p.m. 1700
				20 Feb	78 a.m.	600		
14 Feb 76	1100	8 Feb 77	2300	20 Feb	78 p.m.	1700	10 Feb 79	1800
15 Feb 76	1100	9 Feb 77	2400	21 Feb	78 a.m.	1200	11 Feb 79	2200
16 Feb 76	1100	10 Feb 77	2400	21 Feb	78 p.m.	1600	12 Feb 79	
17 Feb 76	1200	11 Feb 77	2600	22 Feb		1600	13 Feb 79	
18 Feb 76	1300	12 Feb 77	2600	23 Feb		1400	14 Feb 79	
19 Feb 76	1300	13 Feb 77	2600	23 Feb	-	1100	15 Feb 79	
20 Feb 76	1300	14 Feb 77	2600	24 Feb		1600	16 Feb 79	900
21 Feb 76	1600	15 Feb 77	2600	25 Feb		1600	17 Feb 79	
22 Feb 76	1600	16 Feb 77	2300	26 Feb		1600	18 Feb 79	1000
23 Feb 76	1500 1400	17 Feb 77	2600	27 Feb		1400	19 Feb 79	
24 Feb 76		18 Feb 77	2600	28 Feb		1400	19 feb 79	•
25 Feb 76 a.m 25 Feb 76 p.m		22 Feb 77 23 Feb 77	2300	28 Feb	'	1900	20 Feb 79	
26 Feb 76	1400	23 Feb 77 24 Feb 77	2000 2400		78 a.m. 78 p.m.	1600 1900	21 Feb 79	1000
27 Feb 76	1600	25 Feb 77	2600	2 Mar		1700	22 Feb 79 23 Feb 79	1300 1000
_, 125 ,0	.000	22 KEU //	2000	- mar		1,00	~J reD /7	1000

1975-197	'6		19	76-	1977			197	77-197	78		19	78-	-1979	
	cation ft)	Dat	:e		Location (ft)	Dat	e		Lo	cation (ft)	Dat	e			ation ft)
		28 1 2 3 4 7 8 9	Feb Mar Mar Mar Mar Mar Mar Mar	77 77 77 77 77 77 77		3 3 4 4 5 6 7 8 8 9 10 10 11 11 11 12 13 14	Mar Mar Mar Mar Mar Mar Mar Mar Mar Mar	78 78 78 78 78 78 78 78 78 78 78 78 78	a. m. p. m. a. m. p. m.		244 255 255 266 277 288 1 2 3 4 4 5 6 6 7 8 9 10 11 12 13	Feb Feb Feb Mar Mar Mar Mar Mar Mar Mar Mar Mar Mar	79 79 79 79 79 79 79 79 79 79 79 79	a.m.	1100 1200 600 800 1000 1200 1200 1200 1400 1600 1700 1700 1700 1700 1200 2600
18 Mar 76 19 Mar 76 20 Mar 76 21 Mar 76 21 Mar 76 22 Mar 76 23 Mar 76 23 Mar 76 24 Mar 76 24 Mar 76 26 Mar 76 27 26 Mar 76 27 27 28 Mar 76 29 30 30 30 30 30 30 30 30 30 30 30 30 30	1800 1800 n. 1600 n. 1800 n. 1800 on 2900					18 18 19		78 78 78	a.m. p.m.	5600 5600 10500 5300 11600	14 15 16 17 18 19		79 79 79 79 79 79	a. m.	2900 2000 2000 1800 1800 2800 5300 11600
Avg. upstream	na 1570				2340					1990					1530

APPENDIX B. ESTIMATE OF ICE THICKNESS IN LITTLE RAPIDS CUT

An unconsolidated ice cover is held in position by forces from the riverbanks and a stable ice cover downstream. The natural forces that move the floating ice cover are hydraulic flow forces, wind drag, ice weight and moving ice impinging on the ice edge. Because the ice is fragmented, longitudinal (downstream) forces tend to cause it to move laterally, and this is resisted by the riverbanks. Therefore, compressive forces develop in both the lateral and the longitudinal directions; if the forces are large enough, the cover will thicken until the internal material stresses are sufficiently reduced. Under some circumstances the ice cover will also thicken from deposits of ice fragments drawn under the ice edge by water currents.

Theoretical relationships have been developed through field and laboratory research for predicting the thicknesses of unconsolidated ice
covers. Researchers have found that when a river is narrow, the thickness
is controlled by conditions at the ice edge. When a river is fairly wide,
however, the path of compressive stresses, or arch, becomes long, and to
remain stable the ice cover must become thicker than it would need to be if
the river was narrower.

The river discharge at Frechette Point flows primarily through Little Rapids Cut. A small portion of the flow, however, comes down the natural channel between Island No. 1 and Sugar Island (Little Rapids). A portion of the flow that comes into the Little Rapids Cut branches off to pass between Islands No. 3, 2 and 1 (lower end). The depth varies along these alternate water routes; a rough estimate of their combined average flow area is 465 m² (5000 ft²), which is a significant value. Their effect on the overall flow can only be generalized.

The discharge in Little Rapids Cut is highest just below the ferry track. Upstream of Island No. 2 some of the flow is drawn off to pass between Islands No. 2 and 3 and the mainland. At the lower end of Island No. 1 additional flow enters the Little Rapids Channel through the natural Little Rapids reach. The quantity of water entering here is probably substantially less than the water being drawn away above Island No. 2. The flow split is unknown, even under open water conditions. The effects of these parallel channels during the ice progression period are more difficult to estimate because they are ice covered by the time the period occurs.

Table Bl. Data on the upper and lower sections of the Little Rapids Channel during the third week of January 1979.

Section	Location* (ft)	Water surface elevation (ft)	Reference avg. bed elevation (ft)	Average depth (ft)	Channel width (ft)	Flow area (ft ²)
Little Rapids Cut	48+56	580.28	548.94	31.34	757.8	19,319
Frechette Point	145+67	579.68	547.47	32.21	1495	29,133

^{*} Ice boom opening is at 29+25.

Water surface elevations in Little Rapids Channel were measured in Little Rapids Cut immediately downstream of the ice boom and at Frechette Point, at the lower end of the channel. The distance between the two sites is 3,200 m (10,500 ft). The set of conditions used in the following analysis is the weekly average difference in water surface elevations between these two gauge points, or 0.18 m (0.60 ft) with a St. Marys River discharge of 1,897 m³/s (67,000 cfs) for the third week of January 1979. This stage differential is the value when the ice cover first reached Sugar Island ferry track on 20 January 1979. The slope, therefore, is 5.71x10⁻⁵. Other data for this work are summarized in Table B1.

It is difficult to estimate the thickness of the unconsolidated ice cover that develops in the Little Rapids Cut because of the many variables involved. Acres American Inc. (1975) estimated that it would be between 0.9 and 1.5 m thick (3-5 ft). The method of estimation used here is patterned after Beltaos (1983), who carefully reviewed the work of several important American, Canadian and Russian researchers and developed the following relationship (Fig. B2):

$$H = h + s_i t \tag{B1}$$

where

H = water level at the upstream edge of the unconsolidated ice cover

h = water depth beneath the ice cover

t = ice cover thickness

 s_i = ratio of the densities of ice and water.

He showed that the flow depth is

$$h = \left(\frac{q}{\left(\frac{4 - S}{f_0}\right)^{1/2}}\right)^{2/3}$$
 (B2)

where

q = flow per unit channel width

S = slope of the water surface

g = gravitational constant

 f_0 = Darcy Weisback friction factor for the ice-covered channel. The last term is usually considered to be the average of the friction factor for ice f_1 and the friction factor for the riverbed f_b .

Beltaos assumed that the ice mass is cohesionless and determined that the ice cover thickness t is equal to

the ice cover thickness t is equal to
$$t = \frac{WS}{2\mu(1-s_1)} \left\{ 1 + \left[1 + \frac{(2 f_0)^{1/3} \mu(1-s_1)}{s_1} \left(\frac{f_1}{f_0} \right) \frac{(\frac{q^2}{gS})}{WS} \right]^{1/2} \right\}$$
(B3)

where W is the channel width and μ is the product of the angle of internal friction of the ice mass and the coefficient of lateral thrust of the accumulation. Beltaos recommended the use of μ = 1.2 and s_1 = 0.92.

No values of f_0 for the ice-covered Little Rapids Channel are available. Data were available in my files, however, for the Beauharnois Canal, which is a man-made navigation and diversion canal of similar depth for the St. Lawrence River near Montreal, Canada. Values of f_0 were calculated for the times when the unconsolidated ice cover first became complete in early winter on the canal; data for six years (1974-1980) were available. The values of f_0 varied from 0.05 to 0.07 and had an average of 0.058. The average flow velocity in the canal was 0.59 m/s (1.92 ft/s).

The Corps of Engineers hydraulics survey crew made extensive surveys of flows and flow areas at Frechette Point and at the Old North Channel (Table B2). If the Little Rapids Cut properties apply (if its flow is 69% of 1,897 $\rm m^3/s$ [67,000 cfs] and if $\rm f_1/f_0$ equals 1), the value of H calculated from the Beltaos equations is 10.2 m (33.6 ft), which is much higher than the actual depth of 9.54 m (31.3 ft). If one further assumes that approximately 10% of the flow passes around the small islands adjacent to Little Rapids Cut, then the calculated and the actual water elevations

Table B2. Flow distribution around Sugar Island.

Condition	Little Rapids Channel	Old North Channel
Open water	71-76%	29-24%
Ice covered	64-69%	36-31%

match quite well. The average flow through the cut then is $1,174 \text{ m}^3/\text{s}$ (41,470 cfs), the average velocity is 0.66 m/s (2.15 ft/s), and the estimated ice thickness is 0.88 m (2.9 ft).

This estimate accounts only for the natural effects of water currents on the unconsolidated ice cover and is the minimum thickness that one would expect to find in the Cut without shipping. The effects of icebreakers and transports could cause the ice cover to become even thicker but by an unknown amount. Based on these factors, it is assumed that the ice cover in the Little Rapids Cut is at least 0.91 m (3 ft) thick.

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